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Research and Modeling of the Finishing Method of Cylindrical Gear Teeth Through Cold Plastic Calibration

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***Abstract*—The operational performance of gearwheels is largely determined by the accuracy of the parameters and the quality of the working surfaces of the teeth, the requirements for which are constantly increasing. To optimize the machining conditions (increasing productivity, tool durability and the quality of the machined gearwheels), a method for finishing machining by calibration on gear-shaving and thread-rolling machines is proposed in the work. Experimental studies have been conducted to prove the operability of the proposed method. The results obtained have been analyzed and compared with gear-milled gearwheels in terms of kinematic accuracy, smoothness of operation and contact of the teeth. Regression models have been obtained for the accuracy parameters of the teeth before and after processing by calibration and subsequent heat treatment, the analysis of which shows that their size is largely determined by their input values. The results of the studies confirm the assumption of the presence of a correlation between the same accuracy parameters at the input and at the output during processing by calibration and subsequent heat treatment.**

Keywords*—*calibration, gear-shaving machines, thread-rolling machines, accuracy.

I. INTRODUCTION

In today's complex environment and in the conditions of Industry 4.0, engineering companies are required to make great efforts to maintain their competitiveness in the domestic and foreign markets and constantly seek solutions for higher efficiency and productivity [1] - [3]. The practice of industrially developed countries has long proven that one of the preferred solutions is the development of progressive methods for processing the surfaces of parts, determining their operational characteristics.

The operational performance of gearwheels is largely determined by the accuracy of the parameters and quality of the working surfaces of the teeth, the requirements for which are constantly increasing. This results from the sharp increase in the peripheral speeds, transmitted power, accuracy, as well as the need for their reliability and durability in production conditions, with optimal metal consumption. This leads to the need of conducting research, related to improving the qualities of gearwheels and gear trains.

One of the directions is to develop progressive methods for finishing gear teeth based on reconstruction of existing universal machines or adding special attachments to them, which can be manufactured and maintained by tool-shops of medium capabilities [4] - [6].

One such method is calibration, in which the teeth are processed by surface plastic deformation, using the property of metals to deform plastically in their cold state [4], [7]. Hardened gear rollers are used as deforming elements, which roll the workpiece with pre-cut teeth. The axes of the machined wheel and the gear rollers are parallel, and the machining is performed with gradual reduction of the center distance between the teeth.

Under the action of the deforming element, the micro-irregularities, resulting from the previous tooth machining are smoothed out, with the metal moving away from the contact point and filling the adjacent recesses. Thus, the size of the micro-roughnesses on the machined surfaces decreases, creating micro-irregularities, qualitatively different from those, resulting from machining by material removal. This method allows to obtain teeth with low roughness and increased ability to retain a continuous oil layer.

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In calibration there is an opportunity to significantly increase the contact surface, which leads to lower contact stresses and reduced noise when the tooth pair is in operation. The surface metal layers get strengthened and their hardness increases at a certain depth, while the main part of the metal remains with a high impact toughness; residual compressive stresses arise; and, in result, gearwheels with improved strength and operational performance are obtained.

The aim of the present work is to study and model the quality indicators of the teeth of cylindrical gearwheels, machined through calibration in order to substantiate the real possibility for commercial implementation of the calibration method as a method for tooth finishing processing.

II. MATERIALS AND METHODS

The engagement without lateral clearance between the machined gearwheel and the tool in the calibration process is performed along two crossed tangents to the main cylinders of the part and the tool (the engagement lines), one of which starts from the tooth head of the part and passes through the engagement pole to the tooth base, machining one side of the tooth, the driven one. On the reverse side of the tooth, the engagement occurs from the base to the head of the tooth. The sliding motion of the lateral surfaces of the teeth, relative to each other, causes material accumulation (in the direction from the tooth head and base towards the dividing cylinder) on the driven teeth surfaces of the machine part (Fig.1). In result, material compression occurs along the dividing cylinder and, on the reverse side of the tooth, material is removed from the dividing cylinder towards the base and head of the tooth. As a consequence, the outer diameter of the wheel increases.

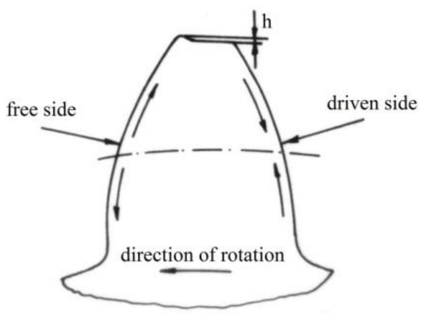

Fig. 1. Material displacement in the process of tooth machining by calibration.

The conditions for implementing the calibration process are related to:

- *The choice of a machine,* which allows: the radial feed of the tool to be limited with great accuracy; synchronous rotation of the calibration gearwheels; a possibility to disengage and center the calibration gearwheels depending on the number of teeth of the workpiece; a possibility to adjust the radial force.
- *The tool material:* with individual for each particular case thermal treatment and accuracy; with high hardness and impact toughness of the working surfaces.
- *The material of the blanks* – the hardness of the workpieces should not be greater than HB 220.

In order to optimize the conditions of machining (to increase productivity, tool durability, and improve the quality of the machined gearwheels) a tool has been proposed and a method for finishing machining by calibration on gear-shaving machines has been implemented by the Department of Mechanical Engineering Equipment and Technologies at the Technical University of Gabrovo.

Experimental studies were conducted by machining 60 gearwheels, made of 41Cr4 steel with a hardness of HRC18, divided into 12 groups of 5, by calibration on a semi-automatic gear-shaving machine 5702B with the following tooth parameters: m = 3mm; z = 52; β_d = 14°04'; b = 25mm.

The tooth parameters were measured before and after processing by calibration:

- to assess the kinematic accuracy – the differential indicators: radial chatter of the gear ring Frr and fluctuation in the base tangent length FVwr;
- to assess the smoothness of operation – the deviation from the tooth profile *ffr;*
- to assess the contact between the teeth - the deviation from the direction of the teeth *Fβr*;
- roughness of the working surfaces;
- surface layer hardness.

The control and measurement of the obtained quality indicators was carried out with: a normometer (with an accuracy of 0.01 mm), a gear tooth measuring machine PFSU 640 (KLINGELBERG - Germany), a TESA Rugosurf 20 profilometer and a "NEQFOT-2" microhardness tester.

The calibrating carbide tools had the following parameters: m = 3 mm; z = 53; accuracy grade - 6 (ENBDS3296), hardened to HRC58...60 and with roughness of the working surfaces Ra = 0,32µm.

The preliminary processing of the teeth before calibration is milling with a worm modular cutter on a 5K310 gear-milling machine.

To establish a rational operating mode, preliminary single-factor experiments were conducted. Based on them, the following were adopted: tool rotation frequency $n = 100\ min^{-1}$, longitudinal feed $V_f = 35\ mm/min$, radial feed $f_p = 0,14;\ 0,04;\ 0,02;\ 0\ mm$ at number of strokes $p = 4$.

III. RESULTS AND DISCUSSION

The obtained results of the measurements, made before (curves 1) and after (curves 2) processing by calibration, are presented graphically in Fig. 2.

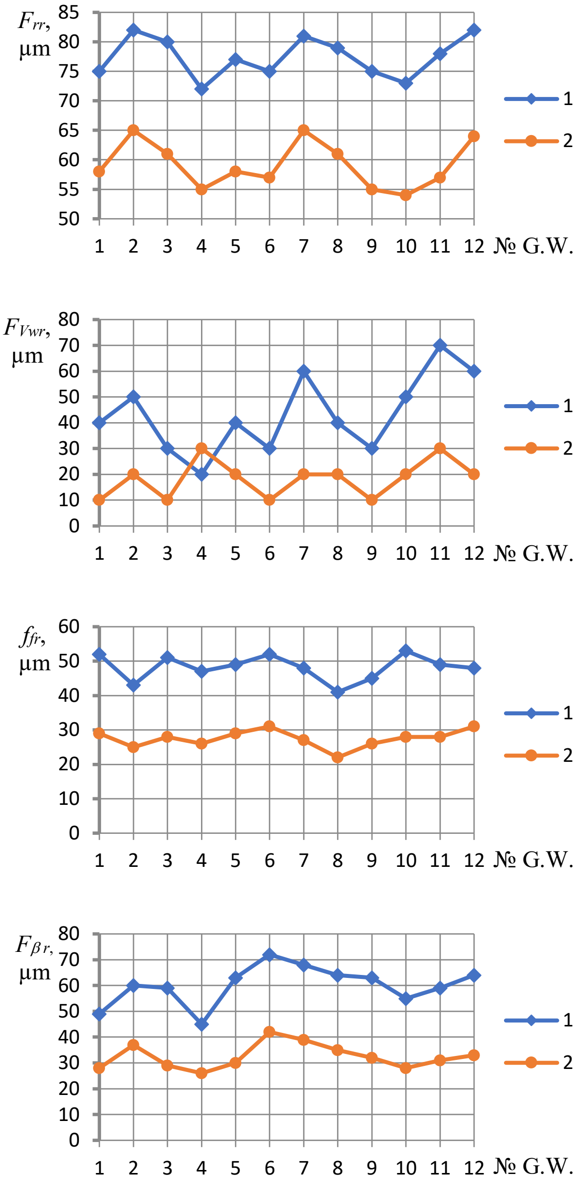

Fig. 2 Results from the experimental studies.

The graphs show that the accuracy of the studied parameters increases by an average of 1.5 to 3 times. To achieve higher accuracy for f_{fr} and $F_{\beta r}$ (Fig. 2), it is necessary to distribute the most of the allowance to the tooth head, since with an increase in f_p, the thickness of the tooth head becomes thinner, which leads to an increase in the deviations f_{fr} and $F_{\beta r}$. If this condition is met, a reduction of f_{fr} and $F_{\beta r}$ from 3 to 6 times can be achieved.

A barrel-like shape is obtained along the direction of the tooth, which is favorable when the axes of the assembled gear train are not parallel. A significant reduction in the roughness is obtained on the lateral surfaces of the teeth (up to $R_a = 0,16$ *µm*, while with shaving the roughness is $R_a = 0,63$ *µm)*. The surface hardness of the working surfaces of the teeth also increases, which is favorable for non-heat-treated gearwheels, and subsequent thermal and chemical-thermal treatment results in more uniform phase changes and saturation.

The deformation rate depends on V_f (at a low rate of deformation, the tool acts on the machined surfaces for a longer time and the plastic deformation spreads to a greater depth, making it necessary in practice to work with a higher deformation rate, as this leads to higher productivity).

Productivity increases up to 2 times, since the allowance during calibration is deformed for 3÷4 longitudinal strokes, while in a process of shaving it is removed for 6÷8 strokes.

The durability of the carbide calibrating tools is 6÷8 times greater than the durability of the high-speed steel shavers (the increase in tool durability is explained not only by the carbide design of their teeth, but also by the replacement of the sliding friction during shaving with rolling friction during the process of calibration).

It is not possible to apply a large deformation force when processing teeth by calibration on a shaving semi-automatic machine, as this leads to rapid breakage of the supporting elements of both the mandrel and the machine. Therefore, it is necessary to use four working strokes, setting radial feed for three of them (0,14; 0,04; 0,02 mm/stroke), and the fourth stroke performed without radial feed in order to deform the allowance, remaining from the elastic deformations in the technological system.

The company "Troymash" AD Dryanovo owns a thread-rolling machine UPW-25 x 100 (Germany), which can also be used as a tooth-calibrating one.

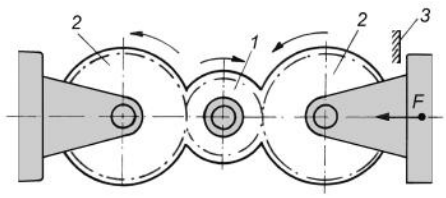

Fig. 3. Scheme of conducting the experimental research.

This machine allows to carry out finishing machining: with two calibrating synchronously rotating gearwheels during radial feed of one gearwheel to the other; with options for sensing and limiting the radial feed of the tool; and with an axial feed of the workpiece for machining the tooth profile across the entire width (Fig. 3). The machine is with a stepless control of the rotation frequency (50÷200min^{-1}) and radial force (≤ 250.10^{3}N), and can be switched on to a semi-automatic or automatic cycle of operation with an accuracy of the center distance ±4.10^{-3}mm.

Experimental studies were carried out on this machine to determine the dependencies between the input values of the different accuracy parameters before calibration, i.e., after tooth milling, and their values at the output of the processes of calibration and heat treatment. Planetary gearwheels from a planetary reducer for electric hoists, made of C45 steel, with a number of teeth $z = 49$ and module $m = 2{,}25\ mm$, were used as objects for research. The accuracy of the gearwheels before and after calibration was evaluated according to the same indicators specified above.

The processing of the experimental data involves two stages. The first stage (preliminary statistical analysis) consists in checking the homogeneity of the samples and the hypothesis of normality of distribution of the studied parameters. The second stage involves finding the mathematical description for the change in gearwheel accuracy after processing their teeth by calibration and heat treatment. Such a description is a polynomial (linear or nonlinear), establishing the relationship between the input and output values of the accuracy parameters. The method of correlation analysis was used to find the model.

The regression model allows to perform a complete statistical analysis of the empirical regression equation. For all studied accuracy parameters, it is established that the correlation between the output and input values is a linear one. Then the regression equation has the form:

$$y = a + bX \tag{1}$$

Table 1 shows the results, concerning the individual accuracy indicators, as well as the regression equations after calibration for input factors of tooth milling.

TABLE 1 REGRESSION MODELS AND STATISTICAL ANALYSIS AFTER CALIBRATION

Parameter of accuracy	$\bar{X}$	$\bar{Y}$	S_x^2	S_y^2	r_{xy}	**Equation of regression**
F_{rr}	0,1122	0,0768	0,00148	0,00120	0,845	$\hat{Y}$=0,0086+0,7615X
F_{Vwr}	0,0288	0,0272	0,00249	0,00111	0,766	$\hat{Y}$=0,0125+0,5119X
f_{fr}	0,0577	0,0364	0,00017	0,00002	0,466	$\hat{Y}$=0,0261+0,1799X
$F_{\beta r}$	0,0553	0,0335	0,00017	0,00010	0,630	$\hat{Y}$=0,0067+0,4834X

The regression equations determine the magnitude of the error in the output depending on the error in the input. The coefficient b in these equations shows what part of the error at the input is transferred to the output, and the free member a – the magnitude of the error, obtained during the execution of the given operation. A criterion for the strength of the relationship between the same accuracy parameters before and after calibration is the coefficient of correlation r_{xy}.

The regression analysis shows that the free member in the regression equations for the parameters F_{rr}, F_{Vwr}, f_{fr} and $F_{\beta r}$ is insignificant, i.e., the error, obtained during the execution of the calibration operation is insignificant and can be ignored. Since in all equations the coefficient b is in the range $0<b<1$, from here it follows that for the studied parameters partial correction of the output error occurs. The correction is the smallest for the parameter F_{Vwr}, and the largest – for f_{fr}. In the latter case, an error occurs during the execution of the operation itself, equal to 0,026 mm.

As a result of the plastic deformation, hardening of the working surfaces of the teeth occurs (at a depth of up to 0,05 mm), which results in strengthening the material and increasing its hardness (up to 70.10^8 N/m^2). Greater hardness is obtained on the driven side, where the material is compressed against the dividing cylinder of the gearwheel.

The roughness of the working surfaces of the teeth reaches $R_a = 0{,}16\mu m$ and is an indicator of the noise and efficiency of the gear trains.

The experiments conducted showed the real possibility to implement finishing machining of gearwheels by cold plastic calibration in manufacturing.

During the heat treatment of the gearwheels after the calibration operation, an increase in the values of the individual parameters is observed, which is also reflected in the regression equations shown in Table 2.

The studies show that after heat treatment the actual dispersion field expands for all studied parameters of accuracy.

TABLE 2 REGRESSION MODELS AND STATISTICAL ANALYSIS AFTER HEAT TREATMENT

Parameter of accuracy	$\bar{X}$	$\bar{Y}$	S_x^2	S_y^2	r_{xy}	**Equation of regression**
F_{rr}	0,0768	0,0863	0,00120	0,00125	0,981	$\hat{Y}$=0,0094+1,001X
F_{Vwr}	0,0272	0,0505	0,00111	0,00133	0,923	$\hat{Y}$=0,0206+1,101X
f_{fr}	0,0364	0,0413	0,00016	0,00017	0,948	$\hat{Y}$=0,0086+0,9786X
$F_{\beta r}$	0,0335	0,0452	0,0015	0,00145	0,933	$\hat{Y}$=0,0076+1,122X

IV. CONCLUSION

A relationship has been established between the values of the accuracy parameters of the teeth of cylindrical gearwheels before and after processing by calibration and subsequent heat treatment, with the magnitude of all studied accuracy parameters being largely determined by their input values. The results of the research confirm the existence of a correlation between the same accuracy parameters at the input and output when processing by calibration and subsequent heat treatment.

After machining by calibration, the parameters of accuracy for the gear teeth are improved, except for the length of the base tangent.

The obtained regression models allow the tolerance of the accuracy parameters to be distributed between the mechanical and thermal processing and thus to avert waste.

The roughness of the calibrated tooth surfaces is improved by 3 to 6 times.

The hardness of the surface layer increases 1,5 times after calibration, and 2,1 times after subjecting the workpieces to calibration and heat treatment (with the existing technology - shaving and heat treatment by high-frequency current (HFC) - the hardness of the surface layer increases 1,5 times).

The research shows that calibration can also be applied to finishing the teeth of cylindrical gearwheels.

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